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## **B, $\Lambda_b$ and Charm Results from the Tevatron**

Farrukh Azfar

*Oxford University, Particle Physics Sub-department, 1 Keble Road, Oxford OX1 3RH, UK*



### ABSTRACT

Recent results on  $B_d$ ,  $B_u^\pm$ ,  $B_s$ ,  $\Lambda_b$  and Charm hadrons are reported from  $\approx 75\text{pb}^{-1}$  and  $\approx 40\text{pb}^{-1}$  of data accumulated at the upgraded CDF and D0 experiments at the Fermilab Tevatron  $\bar{p}-p$  collider, during Run-II. These include lifetime and mass measurements of  $B$  and Charm hadrons, searches for rare decays in charm and  $B$  hadrons and CP-violation in Charm decays. Results relevant to CP-violation in  $B$ -decays are also reported.

## 1 Tevatron $p - \bar{p}$ collider and performance during Run-II

The Tevatron  $p - \bar{p}$  collider is being used for extended data-taking for the second time in 10 years. During the period between 1992 and 1996 (Run-I) an integrated luminosity of  $110\text{pb}^{-1}$  was delivered; the goals for the current period starting May 2001 (Run-II) are  $2\text{fb}^{-1}$ , which is a  $\times 20$  increase over Run-I. The upgrades for Run-II consist of a new injection stage delivering more protons, an increased  $\bar{p}$  transfer efficiency and a  $\bar{p}$  recycler (undergoing commissioning) that uses remaining  $\bar{p}$  from the previous store. A table of Run-I and Run-II operating parameters is given in table 1. The peak luminosity, though improving, is still  $\times 4$  below target.

Table 1: *Tevatron Performance Improvement Run-I vs. Run-II.*

	Collision Rate	Bunches	Center of Mass Energy	Peak Luminosity
Run-I:	$3.5\mu\text{s}$ (Run-I)	6x6	$1.8\text{ TeV}/c^2$	$2.4\times 10^{31}$
Run-II:	396 ns	36x36	$1.96\text{ TeV}/c^2$	$4.4\times 10^{31}$

## 2 $B$ Physics at Hadron Colliders: The CDF and D0 Detectors

The  $b\bar{b}$  production cross section  $\sigma(b\bar{b})$  is  $\approx 150\mu\text{b}$  at  $p - \bar{p}$  at the Tevatron, 1 nb at the  $\Upsilon(4s)$  and 7 nb at the  $Z_0$ . All  $B$ -hadrons are produced at the Tevatron (unlike the  $B$  factories), the drawback being the inelastic cross section which is  $1000\times\sigma(b\bar{b})$  making online data selection crucial.

The CDF [1] and D0 detectors [2] have been described elsewhere. In order to utilize the high  $b\bar{b}$  production cross section clean signatures of  $B$  hadron decays must be used when selecting data online. During Run-I CDF used the clean signatures of  $B \rightarrow J/\psi \rightarrow \mu^+\mu^-$  and the decays of  $B$  hadrons to high transverse momentum ( $P_T$ ) leptons. Now the long lifetime of  $B$  hadrons is being utilized at CDF, events containing  $\geq 2$  tracks with high impact parameters ( $d_0$ ) consistent with being daughters of  $B$  hadrons are selected using the Silicon Vertex Trigger, events selected in this way are categorized as “hadronic  $B$  trigger” or “displaced track trigger” events. Another trigger used for  $B$  selection selects events requires the presence of a single high  $P_T$  lepton and a high  $d_0$  track, this is called the “lepton+SVT trigger” or “lepton+displaced track trigger”. The high  $d_0$  triggers have allowed CDF to significantly advance its  $B$  and charm physics capability, now CDF can reconstruct  $B$  decays to fully hadronic final states as well as use the conventional  $J/\psi$  and high  $P_T$  lepton triggers.

The D0 experiment utilizes the  $\mu^+\mu^-$  signature to select  $J/\psi$ s (which may be prompt or long-lived—coming from  $B$  hadrons). D0 triggers also use  $B$  decays to high  $P_T$  leptons. With the advent of a magnetic field and a completely new tracking system D0 has acquired a whole new capability in  $B$  physics and several  $B \rightarrow J/\psi X$  decay modes have been observed during Run-II. The D0 experiment is on its way to introducing a hadronic  $B$  trigger that uses online silicon pattern recognition to select tracks with high  $d_0$ , this will be a welcome addition to D0’s already enhanced capability in  $B$  physics.

### 3 Physics Results: Testing Heavy Quark Expansion: Lifetimes of $B$ Hadrons at CDF and D0

Precise measurements of lifetimes of  $B$  hadrons allow tests of the Heavy Quark Expansion (HQE) which predicts the following hierarchy for  $B$  hadron lifetimes:  $\tau_{B_c^\pm} < \tau_{\Lambda_b} < \tau_{B_d} \approx \tau_{B_s} < \tau_{B_u^\pm}$ . Both CDF and D0 are working toward precision tests of this theory.

#### 3.1 Charged to Neutral Lifetime Ratio of $B$ Hadrons, and $B_s$ Lifetime from fully reconstructed decays

The ratio of the lifetimes of  $B_u^\pm$  to  $B_d$  has been measured at CDF, and the  $B_u^\pm$  lifetime has been measured at D0 using fully reconstructed  $B_d \rightarrow J/\psi K^*$  and  $B_u^\pm \rightarrow J/\psi K^\pm$  decays. The decays are fully reconstructed, the invariant mass and proper decay length ( $c\tau$ ) distributions of the  $B$ s are calculated from an un-binned log-likelihood function determining both mass and lifetime in a single fit. The result is  $1.11 \pm 0.09$  at CDF using  $70 \text{ pb}^{-1}$  of data, whereas the  $B_u^\pm$  lifetime has been measured to be  $1.76 \pm 0.24 \text{ ps}$  at D0. Both these measurements test HQE and are consistent with the more accurate measurements at BaBar and Belle.

#### 3.2 $B_s$ Lifetime from the fully reconstructed decay $B_s \rightarrow J/\psi \phi$ , $J/\psi \rightarrow \mu^+\mu^-$ and $\phi \rightarrow K^+K^-$

The world’s largest number of fully reconstructed  $B_s$  decays has been at the Tevatron since Run-I. CDF and D0 has successfully reconstructed this decay using data from their  $J/\psi \rightarrow \mu^+\mu^-$  trigger during Run-II, the reconstructed signals are shown in Fig. 1. A measurement of the lifetime is underway at D0, CDF has measured a ratio of  $\frac{\tau_{B_s}}{\tau_{B_d}} = 0.89 \pm 0.15$  based on  $70 \text{ pb}^{-1}$  collected during Run-II.

Strictly speaking this ratio isn’t what should be tested, since the CP composition of the final state is not known. The final state is a mixture of CP eigenstates,

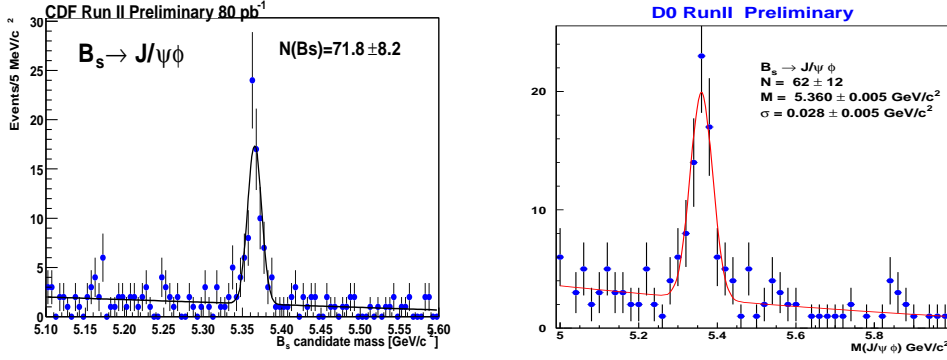


Figure 1:  $B_s \rightarrow J/\psi \phi$  with  $J/\psi \rightarrow \mu^+ \mu^-$  and  $\phi \rightarrow K^+ K^-$  at CDF (72 events) and D0 (61 events)

and the  $B_s$  CP even and odd eigenstates can have a difference in lifetime of upto 10 % as predicted by theory, by fitting a single lifetime in this mode an “average” lifetime has been determined. The relationship between splitting in width (lifetime) of the  $B_s$  CP eigenstates and the  $B_s$  mixing parameter is known in the Standard Model, therefore a measurement of the width (lifetime) difference and mixing parameter provides a test of new Physics. It is planned to measure the lifetime difference of the  $B_s$  CP eigenstates by utilizing angular variables to disentangle the two CP eigenstates and fitting two lifetimes, this approach will become viable with higher statistics. An accuracy of 5 % in determining the lifetime splitting is expected at CDF using 4000  $B_s \rightarrow J/\psi \phi$  decays.

A clean measurement of the width difference  $(\frac{\Delta\Gamma}{\Gamma})_{B_s}$ , can be made by measuring a single lifetime in a decay of the  $B_s$  to a CP eigenstate *e.g.*  $B_s \rightarrow D_s^+ D_s^-$  and  $B_s \rightarrow K^+ K^-$ . This approach is planned as well.

### 3.3 Measurement of the $\Lambda_b$ Lifetime

The  $\Lambda_b$  has been reconstructed at both CDF and D0 in various modes, Fig. 2 shows the reconstruction in the fully hadronic mode at CDF and in  $\Lambda_b \rightarrow J/\psi \Lambda$  at D0.

CDF has also reconstructed  $\Lambda_b$  in the decays  $\Lambda_b \rightarrow J/\psi \Lambda$  (53 events) and  $\Lambda_b \rightarrow \Lambda \ell \nu_\ell$  (640 events) and in the purely hadronic decay mode  $\Lambda_b \rightarrow \Lambda_c^\mp \pi^\pm$  with  $\Lambda_c \rightarrow p K \pi$ . A lifetime measurement has just been completed at CDF using the fully reconstructed decay  $\Lambda_b \rightarrow J/\psi \Lambda$  with a result  $\tau_{\Lambda_b} = 1.25 \pm 0.26(stat) \pm 0.1(syst)$  ps shown in Fig. 3. Work on D0’s  $\Lambda_b$  lifetime currently underway.

The decays  $\Lambda_b \rightarrow \Lambda_c^\pm \ell \nu_\ell$  and  $\Lambda_b \rightarrow \Lambda_c^\pm \pi^\mp$  are selected using a trigger with  $d_0$  cut, the resulting biases in the  $c\tau$  distribution have to be understood before a

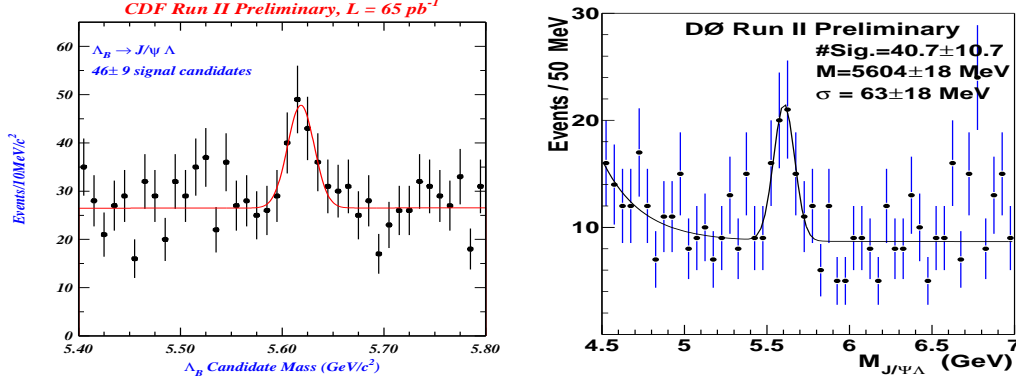


Figure 2: CDF (left) and D0 (right) reconstruction of  $\Lambda_b \rightarrow J/\psi\Lambda$ .

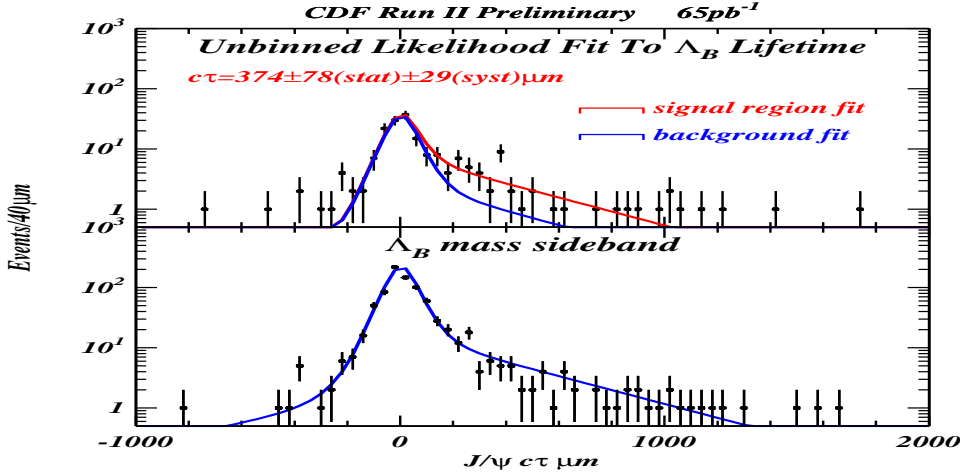


Figure 3: Lifetime distribution of  $\Lambda_b \rightarrow J/\psi\Lambda$  decays at CDF in micro-meters.

lifetime measurement from these modes can be completed and CDF expects this will be done soon.

#### 4 Charm Physics: $D_s^\pm - D^\pm$ mass difference

The first CDF Run-II publication [3] was a measurement of the mass difference  $\Delta M = M_{D_s^\pm} - M_{D^\pm}$ . Both the  $D_s^\pm$  and  $D^\pm$  decay to  $\phi\pi^\pm$  with  $\phi \rightarrow K^+K^-$  with almost identical kinematics. Using data selected by the displaced-track hadronic trigger 2400  $D_s^\pm$  and 1600  $D^\pm$  were reconstructed using only 11.6 pb<sup>-1</sup> of data. The measurement of  $\Delta M = 99.28 \pm 0.43(stat) \pm 0.27(syst)$  MeV/c<sup>2</sup> is consistent with the current world average [16] of  $99.2 \pm 0.5$  MeV/c<sup>2</sup>.

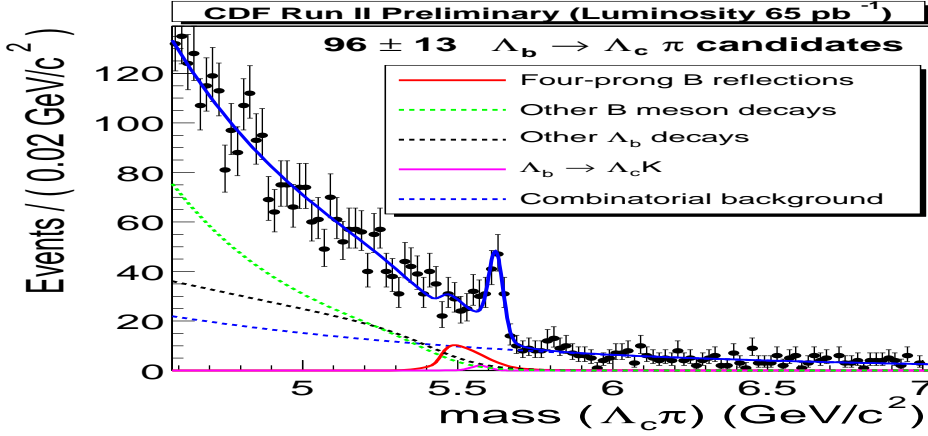


Figure 4: *Invariant Mass distribution of the purely hadronic  $\Lambda_b$  decay mode  $\Lambda_b \rightarrow \Lambda_c^\pm \pi^\mp$  at CDF.*

## 5 Rare Decays: The Search for the Flavour Changing Neutral Current Decay $D \rightarrow \mu^+ \mu^-$ and $B_s \rightarrow \mu^+ \mu^-$

The standard model predicts a branching ratio of  $O(10^{-13})$  for the decay  $D^0 \rightarrow \mu^+ \mu^-$  via second order weak interactions. Some R-parity violating SUSY models predict branching ratios  $\leq O(10^{-6})$  [10]. CDF has searched for  $D^0 \rightarrow \mu^+ \mu^-$  decays using hadronic trigger data and  $D^0 \rightarrow \pi^+ \pi^-$  decays which have almost identical acceptance and kinematics to  $D^0 \rightarrow \mu^+ \mu^-$ . The probability of a  $\pi^\pm$  faking a  $\mu^\pm$  must be calculated, unambiguously identified pions are obtained using the decay chain  $D^{*\pm} \rightarrow D^0 \pi^\pm$ ,  $D^0 \rightarrow K^\mp \pi^\pm$ , the charge of the  $\pi^\pm$  from the  $D^{*\pm}$  determines the flavour of the  $D^0$  and distinguishes the  $K^\pm$  from the  $\pi^\pm$ . The number of times a  $\pi^\pm$  is reconstructed as a  $\mu^\pm$  is determined after which  $D^0 \rightarrow \mu^+ \mu^-$  are reconstructed and expected number of  $D^0 \rightarrow \pi^+ \pi^-$  decays faking  $D^0 \rightarrow \mu^+ \mu^-$  is subtracted, 0 events are found in a  $2\sigma$  search window. A limit for this branching ratio  $\leq 2.4 \times 10^{-6}$  is calculated at 90 % confidence level, better than the best published limit of  $4.1 \times 10^{-6}$  [11] [16].

CDF has done a similar analysis of the decay  $B_s \rightarrow \mu^+ \mu^-$  using 113  $\text{pb}^{-1}$  of Run-II data. Standard Model prediction for the branching ratio is  $3.8 \pm 1 \times 10^{-9}$ . Various SUSY models [13] allow for an enhancement by a factor of upto  $\times 10^3$ , areas of m-SUGRA space that overlap those predicting deviations of the  $g_\mu$  from 2 are roughly consistent [14] with recent experimental measurements [15]. CDF's measurement yields limits  $BR(B_s \rightarrow \mu^+ \mu^-) < 9.5 \times 10^{-7}$  and  $1.2 \times 10^{-6}$  at the 90 % and 95 % confidence intervals respectively—a factor of 2 better than the best

previous measurement [16].

## 6 CP Violation in Charm Decays

The Standard model prediction for CP violation in charm decays is of order 0.1-1 %. Since  $c$  and  $u$  quarks do not couple to  $t$  quarks, box diagram contributions to mixing in charm are tiny, and so CP violation in Charm decays is almost entirely due to interference in decay (direct CP violation). A search for CP violation in charm decays has been done at CDF. Rates of decays of  $D^0$  and  $\bar{D}^0$  decaying to the CP eigenstates  $f = K^+K^-$  and  $f = \pi^+\pi^-$  are measured. The flavour of the  $D^0$  is tagged as described in section 5, and  $D^0 \rightarrow \pi^+\pi^-$  and  $\rightarrow K^+K^-$  decays are reconstructed and counted and the asymmetry

$$A_{CP} = \frac{\Gamma(D^0 \rightarrow f) - \Gamma(\bar{D}^0 \rightarrow f)}{\Gamma(D^0 \rightarrow f) + \Gamma(\bar{D}^0 \rightarrow f)} \quad (1)$$

for each mode is calculated. The results are  $A_{CP}(D^0 \rightarrow \pi^+\pi^-) = 2.0 \pm 1.7(stat) \pm 0.6(syst) \%$  and  $A_{CP}(D^0 \rightarrow K^+K^-) = 3.0 \pm 1.9(stat) \pm 0.6(syst) \%$ , consistent with both the world averages of  $0.5 \pm 1.6 \%$  and  $2.1 \pm 2.6 \%$  [16] and better than the most recent (2001) CLEO results of  $0.0 \pm 2.2 \pm 0.8 \%$  and  $1.9 \pm 3.2(stat) \pm 0.8(syst) \%$  respectively [4].

As a check of possible biases in counting, the ratios of branching ratios:  $\frac{\Gamma(D^0 \rightarrow K^+K^-)}{\Gamma(D^0 \rightarrow K^\pm\pi^\mp)}$  and  $\frac{\Gamma(D^0 \rightarrow \pi^+\pi^-)}{\Gamma(D^0 \rightarrow K^\pm\pi^\mp)}$  were also calculated and found to be  $9.38 \pm 0.18(stat) \pm 0.10(syst) \%$  and  $3.686 \pm 0.076(stat) \pm 0.036(syst) \%$  respectively. These compare well with the measurements at FOCUS [6]  $9.93 \pm 0.14(stat) \pm 0.14(syst) \%$  and  $3.53 \pm 0.12(stat) \pm 0.06(syst) \%$ .

## 7 Towards CP violation in $B$ -hadron decays and $B_s$ mixing

In Run-I the CDF was able to competitively measure the  $B_d$  mixing parameter  $(\frac{\Delta M}{\Gamma})_{B_d} = x_d$  and also perform a  $2\sigma$  measurement of the CP asymmetry in the decay  $B_d \rightarrow J/\psi K_S$  ( $\sin 2\beta$ ) [9]. The Run-I measurement was  $\sin 2\beta = 0.79 \pm 0.39(stat) \pm 0.16(syst)$ , BaBar and Belle already have measurements of  $0.76 \pm 0.067(stat) \pm 0.034(syst)$  and  $0.733 \pm 0.057(stat) \pm 0.028(syst)$  respectively [7] [8]. With  $\times 40$ -50 more decays expected when  $2 \text{ fb}^{-1}$  have been accumulated, CDF's precision should be  $\delta(\sin 2\beta) \approx 0.05$ , D0 should have similar statistics. Clearly D0 and CDF cannot compete with the  $B$ -factories  $\sin 2\beta$  measurement, but  $\sin 2\beta$  will be measured as a benchmark, and a test of various flavour tagging schemes.

Various tagging schemes are under examination at CDF; including jet-charge, opposite and same-side tagging and using time of flight to identify  $K$ s. A final number for the statistical power *i.e.*  $\epsilon D^2$  has not yet been calculated using data.

### 7.1 Measurement of $\sin 2\gamma$ using $B_d \rightarrow \pi^+\pi^-$ and $B_s \rightarrow K^+K^-$

Both tree and penguin graphs contribute to  $B_d \rightarrow \pi^+\pi^-$  and  $B_s \rightarrow K^+K^-$  with the tree dominating in the former and the penguin in the latter. Without the penguin contributions the CP asymmetry ( $A_{CP}$ ) in  $B_d \rightarrow \pi^+\pi^-$  is proportional to the CKM quantity  $\sin 2(\gamma + \beta)$  and  $A_{CP}$  in  $B_s \rightarrow K^+K^-$  is proportional to  $\sin 2\gamma$ . Assuming **SU(3)** symmetry and interchanging  $s$  and  $d$ , the hadronic matrix element penguin to tree ratios are the same, the mixing and decay induced  $A_{CP}(t)$  are functions of  $\sin 2\gamma$ ,  $\sin 2\alpha$ ,  $\sin 2\beta$ , the ratio of the hadronic matrix element amplitudes and the phase of this ratio. A measurement of the  $A_{CP}$  thus determines  $\sin 2\gamma$  and  $\sin 2\alpha$ . Before measuring this asymmetry the various  $B_d \rightarrow h^+h^-$  and  $B_s \rightarrow h^+h^-$  decays must be separated. Reconstructing  $B_d \rightarrow \pi^+\pi^-$  without clear hadron identification leads to a very broad peak in which the individual modes  $B_d \rightarrow K^\pm\pi^\mp$ ,  $B_s \rightarrow K^\pm\pi^\mp$ ,  $B_d \rightarrow \pi^+\pi^-$  and  $B_s \rightarrow K^+K^-$  are indistinguishable. These can be separated at CDF utilizing  $\frac{dE}{dx}$  using drift chamber charge deposition and kinematical variable separation. CDF has reconstructed  $39 \pm 14$   $B_d \rightarrow \pi^+\pi^-$  and  $90 \pm 17$   $B_s \rightarrow K^+K^-$  decays, the latter is a first observation. The invariant mass distribution of all  $B$  hadrons decaying to  $h^+h^-$  is shown in figure 5.

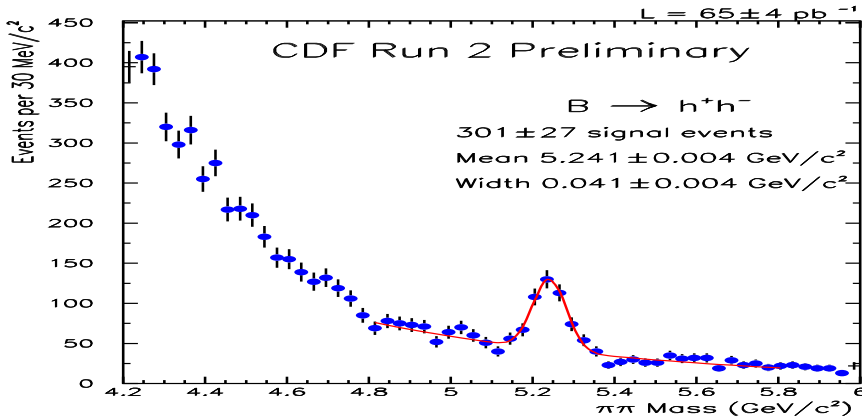


Figure 5: *Invariant Mass distribution of all  $B \rightarrow h^+h^-$ , decays at CDF. Both tracks are assigned the mass of a  $\pi$ .*

As a check the ratio of branching ratios  $\frac{\Gamma(B_d \rightarrow \pi^+\pi^-)}{\Gamma(B_d \rightarrow K^\pm\pi^\mp)}$  has been measured,



the result  $0.26 \pm 0.11(stat) \pm 0.055(syst)$  is consistent with the world-average  $0.253 \pm 0.064$  [16]. The CDF experiment expects to be able to measure  $\gamma$  to an accuracy of  $\sigma(\gamma) \approx 10$  degrees.

## 7.2 Measurement of the $B_s$ Mixing parameter $x_s = \frac{\Delta M_{B_s}}{\Gamma_{B_s}}$

The measurement of the  $B_s$  mixing parameter  $x_s = \frac{\Delta M_{B_s}}{\Gamma_{B_s}}$  is one of the major goals of the Tevatron during Run-II. An observation of the flagship mode for measuring  $x_s$ ,  $B_s \rightarrow D_s^\pm \pi^\mp$  has been made at CDF. In addition to this mode  $B_s$  mixing can also be measured using modes such as  $B_s \rightarrow \mu^\pm \nu_\mu D_s^\mp$  and  $B_s \rightarrow e^\pm \nu_e D_s^\mp$ , however the vertex resolution in these decays is worse due to the missed neutrino. If a single  $B_s$  lifetime is fit in any of these or any flavour specific mode the relation between the fit lifetime  $\tau_{fit}$  and the CP odd and even lifetimes  $\tau_{CP+}$ ,  $\tau_{CP-}$  is  $\tau_{fit} = \frac{(\tau_{CP+}^2 + \tau_{CP-}^2)}{(\tau_{CP+} + \tau_{CP-})}$ , which can be used for a measurement of  $\Delta\Gamma_{B_s}$  and to provide a useful constraint for the two-lifetime fit with  $B_s \rightarrow J/\psi\phi$  described earlier. The first observation of 40  $B_s \rightarrow D_s^\pm \pi^\mp$  decays has been made using hadronic trigger data at CDF, shown in Fig. 6. Also 309  $B_s \rightarrow \mu^\pm \nu_\mu D_s^\mp$  and 245  $B_s \rightarrow e^\pm \nu_e D_s^\mp$  have been observed using lepton+displaced track trigger data.

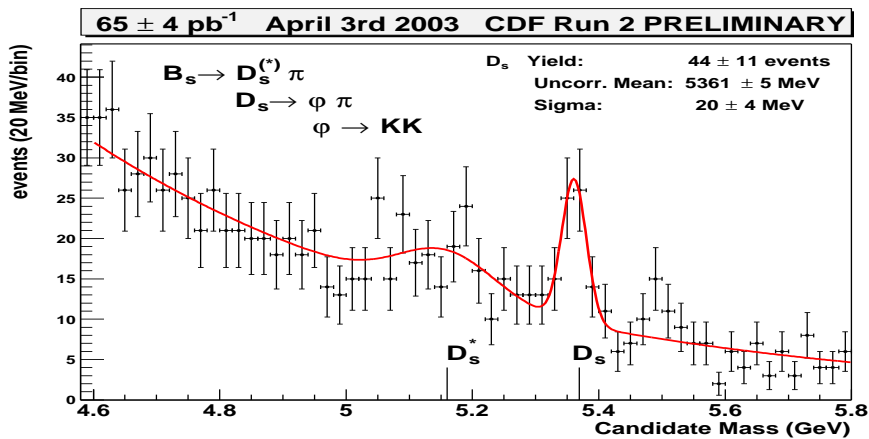


Figure 6: *First observation of  $B_s \rightarrow D_s^\pm \pi^\mp$ , made at CDF.*

## 8 Conclusions

Both CDF and D0 are in the first phase of data taking ( $\int L dt < 200\text{pb}^{-1}$ ) which will test HQE with  $\Lambda_B$  and  $B_s$  lifetimes, and yield limits for CP violation and rare decays in  $B$  and charm decays. Tagging and lifetime measurement techniques (for hadronic trigger data) will also be tested. In the next phase ( $200 < \int L dt < 500\text{pb}^{-1}$ ) limits

on  $B_s$  mixing will be set and CP violation searches in the  $B$  system will be done. In the final phase ( $500 < \int L dt < 2000 \text{pb}^{-1}$ )  $\Delta\Gamma_{B_s}$ ,  $x_s$ , and the CKM angle  $\gamma$  will be measured and finally a search for unexpectedly large CP violation in  $B_s \rightarrow J/\psi\phi$  will be pursued.

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